A 60 Meter Delay Stabilized Microwave Fiber Optic Link for 5.3 GHz Reference Signal Distribution on the Shuttle Radar Topographic Mapper *

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Abstract

JPL has developed a phase stabilized microwave fiber optic link for use on the Shuttle Radar Topographic Mission which is an interferometric Synthetic Aperture Radar system used to map the earth's surface in 3D.

Introduction

The Shuttle Radar Topography Mission (SRTM) will use radar interferometry to map 80% of the earth's surface in 3D in 11 days (Ref. 1). In radar interferometry, two radar images are taken from slightly different locations. Differences between these images allow for the calculation of surface elevation, or change. To get two radar images taken from different locations the SRTM hardware consists of one transmit/receive antenna array in the shuttle payload bay and a receive only antenna array attached to the end of a mast extended 60 meters out from the shuttle. The accuracy of the produced maps partly depends on accurate knowledge of delay variations between the two paths of received signals.

Problem

The problem is that the temperature of the mast and outboard electronics varies as the shuttle flies in and out of the earth's shadow during each orbit. Since cable delay varies with temperature, this results in excessive delay variations in the coaxial cables and outboard electronics that would reduce mapping accuracy. A solution would be to inject a known phase into the inboard and outboard electronics to calibrate out the system phase vs. temperature fluctuations. But any cable that would carry this reference signal along the mast would be affected too. Therefore a self-compensating reference distribution to the outboard had to be designed in order to meet the system requirements.

When in orbit the mast cables will change temperature semi-sinusoidally by as much as 12° C peak-to-peak with a 90 minute orbital period. The average temperature of the cables will be between -10° C and –60° C. Using coaxial cables with the very lowest thermal coefficient of delay (TCD) available still leaves us with a thermal coefficient of delay of up to 40 ppm/°C. In our temperature range the delay change without compensation could be as high as 5 ps. This is equal to 100 degrees of phase at the reference signal frequency of 5.3 GHz. The maximum allowable phase change allocated to the down-link coaxial cable by the system designers is 3 degrees.

Solution

Two approaches to this problem were considered. The first approach was to actively stabilize the delay of the cable through which the received echo signals traveled from the end of the mast back to the shuttle bay. The second approach was to inject a reference tone which would accompany the ground echo signals and be used to later extract the phase of the ground echo signals using computer signal processing of the mission data.

The first approach was abandoned for several reasons. Active delay compensation doesn't work well in a coaxial cable system because of large reflections and low isolation in the system components. Even though delay compensation works very well for fiber optic links, the designers didn't want to risk the use of new technology to carry the received radar signals from the end of the mast back to the shuttle bay. Loss of this link would scrub the mission.

The designers chose to use the second approach. Should the fiber optic link fail, a backup reference tone will be injected, uncompensated into the mast cables, traveling up the mast, then injected back down the mast now to accompany the ground echo signal. The reference tone phase will be assumed to vary by the same amount in the up-mast cable as in the identical down-mast cables and its phase contribution will be extracted accordingly.

To best meet the reliability, bandwidth, and radiation resistance requirements we used a single-mode fiber optic link operating at 1550 nm wavelength.

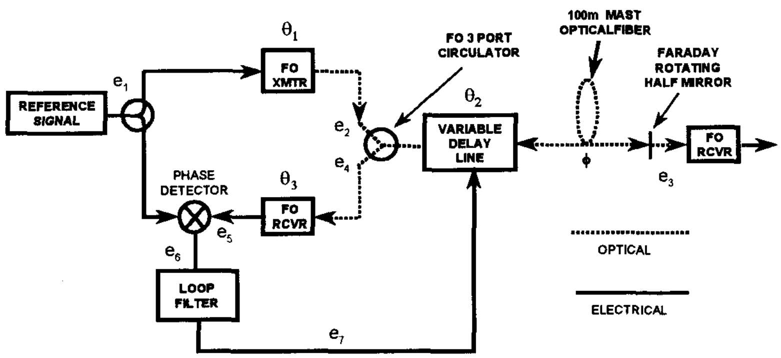

Fig. 1. A block diagram of the stabilized microwave fiber optic link.

Analysis

This is an analysis of the phase relationships in the stabilized fiber optic link. In this analysis the amplitude is not considered. Since the amplitude is not considered, for the sake of simplicity we will also not consider the optical to electrical and electrical to optical conversions. Furthermore we will assume the gain of the negative feedback loop is infinity.

Referring to Fig. 1, the input reference signal is,

$$e_1(t) = A_1 \cdot \sin(\omega \cdot t) \tag{1}$$

This signal, after traveling through a length of cable and the fiber optic transmitter to the fiber optic circulator is,

$$e_2(t) = A_2 \cdot \sin(\omega \cdot t + \theta_1) \tag{2}$$

where, θ_1 = the phase delay between the reference signal generator and the input to the fiber optic circulator.

The signal at the output of the fiber optic cable at the end of the mast is,

$$e_3(t) = A_3 \cdot \sin(\omega \cdot t + \theta_1 + \theta_2 + \Delta\theta_2 + \phi + \Delta\phi) \tag{3}$$

where,

θ_2 = the delay through the variable fiber optic delay line,

$\Delta\theta_2$ = the delay change in the variable fiber optic delay line,

ϕ = the nominal delay of the optical fiber in the mast, and

$\Delta\phi$ = the change in delay of the optical fiber in the mast.

The reflected signal at the return port of the fiber optic circulator is,

$$e_4(t) = A_4 \cdot \sin[\omega \cdot t + \theta_1 + 2 \cdot (\theta_2 + \Delta\theta_2) + 2 \cdot (\phi + \Delta\phi)] \tag{4}$$

The reflected signal at the input of the phase detector is,

$$e_5(t) = A_5 \cdot \sin[\omega \cdot t + \theta_1 + 2 \cdot (\theta_2 + \Delta\theta_2) + 2 \cdot (\phi + \Delta\phi) + \theta_3] \tag{5}$$

where, θ_3 = the phase delay from the reflected port of the circulator through the fiber optic receiver to the phase detector.

The output of the phase detector is the product of (1) and (5),

$$e_6(t) = e_1(t) \cdot e_5(t) \qquad \text{or,}$$

$$e_6(t) = A_6 \cdot \{\cos[\theta_1 + 2 \cdot (\theta_2 + \Delta\theta_2) + 2 \cdot (\phi + \Delta\phi) + \theta_3] + \cos[2 \cdot \omega \cdot t + \theta_1 + 2 \cdot (\theta_2 + \Delta\theta_2) + 2 \cdot (\phi + \Delta\phi) + \theta_3]\} \tag{6}$$

After low pass filtering (6) we get the loop error signal,

$$e_7(t) = A_7 \cdot \cos[\theta_1 + 2 \cdot (\theta_2 + \Delta\theta_2) + 2 \cdot (\phi + \Delta\phi) + \theta_3] \tag{7}$$

It can be shown that there are values for θ_2 that result in (7) being equal to zero. The loop will force θ_2 to one of these values thereby forcing (7) to equal zero. Thereafter, assuming θ_1 and θ_3 are constant, for any change in $\Delta\phi$ the loop will force $\Delta\theta_2$ to change by an equal amount in the opposite direction to keep (7) equal to zero. In other words ($\Delta\theta_2$) will be forced to equal ($-\Delta\phi$).

The result of this is made clear if we substitute ($-\Delta\phi$) for ($\Delta\theta_2$) in (3),

$$e_3(\Delta\phi) = A_8 \cdot \sin[\omega \cdot t + \theta_1 + \theta_2 + \phi + (\Delta\phi - \Delta\phi)] \tag{8}$$

It can be seen that variations in the delay of the optical fiber, $\Delta\phi$, fall out and the phase of the output signal is constant relative to the phase of e_1, the reference signal.

Control Loop Design

We used a thermally controlled spool of optical fiber as a variable delay line. Its design is described in the next section. The relatively long, 180 second, time constant of this complex variable delay complicated the loop design. This delay provided the first pole in the design. Another zero and another pole were added using active electronics. We simulated the response of the loop using SPICE. The control loop design achieved the required acquisition range, tracking range and stability and its simulated performance was verified by extensive testing.

To test the loop's characteristics, we used a network analyzer to measure the phase difference between its input and output. We placed the long mast fiber in an oven and varied its temperature to simulate orbital variations expected in the mission. Because air provides undesired thermal paths that change the time constant of the optical fiber spool, we placed the fiber spool in a vacuum chamber during testing to achieve the in situ thermal response.

A real time data acquisition system collected network analyzer phase and amplitude measurements for analysis.

Photonic Hardware Description

The unique feature of this stabilized fiber optic link is the hardware used to implement it. To our knowledge it is the first use of a 1550 nm single-mode fiber optic system and the first microwave fiber optic system used in a space application. The hardware was, for the most part, commercial-off-the-shelf (COTS). However, it was carefully chosen and modified as needed to operate reliably in the space environment to which it would be exposed. An operating wavelength of 1550 nm was used because the laser was considered to be more reliable and the optical fiber has lower ionizing radiation induced attenuation at this wavelength.

Uniphase Telecommunications Products (UTP) Transmission Systems Division fabricated the stabilized microwave fiber optic link under contract with JPL. This included all of the components shown in the block diagram (Fig. 1) with the exception of the reference signal generator. The fiber optic transmitter module is a slightly modified version of their COTS Small Integrated Transmitter Unit (SITU).

The SITU consists of a 1550 nm high power single-mode CW laser followed by a Mach-Zehnder modulator. The optical output power of the SITU is $\geq$ 5 dBm and the bandwidth is 1-18 GHz. The relative intensity noise (RIN) is $\leq$ -150 dB/Hz and $V\pi$ is $\leq$ 7 volts at 2 GHz. The non-operating temperature range is –55°C to +85°C and its operating temperature is 0°C to +60°C (Ref. 2). The entire stabilized fiber optic system must meet its specifications when the SITU is subjected to any 10°C peak-to-peak temperature variation within the temperature range of +5°C to +45°C.

The 3 port circulator is a COTS device fabricated by E-Tek Dynamics. Its specified wavelength is 1550 nm ± 20 nm. Its insertion loss from 0°C to 60°C is < 1.3 dB over its entire wavelength range. Its minimum peak isolation is 45 dB. The optical return loss is $\leq$ -50 dB.

The FRHM is a modified COTS device fabricated by E-Tek Dynamics. It was modified from a full mirror to a half mirror to allow half of the light to pass through into another optical fiber on the backside of the mirror. Its center wavelength is 1550 nm with a spectral width of 30 nm.

The following table contains typical tests applied to devices fabricated by E-Tek Dynamics (Ref. 3).

Temperature Cycling	-40°C to +80°Cfor 14 days; rate 1°C/min; dwell 1 hour at the extremes
High temperature bake	80°C for 2,000 hours
Vibration	3 axis 20 g's at 20 ~2,000 Hz
Shock	3 axes, 100 g's, 11ms
Max. Tensile Strength	10 N force for 10 seconds

Table 1. Typical tests applied to components by E-Tek Dynamics

The fiber optic photodetector is a COTS device fabricated by Lasertron and is incorporated into the fiber optic receiver unit fabricated by UTP. Its has a 1,000 ohm output resistor and a bandwidth of 0.01 to 12 GHz when loaded with 50 ohms. The spectral range is 1100 nm to 1650 nm. The responsivity is 0.8 A/W at 1300 nm and the optical return loss is ≥ 40 dB. The operating temperature range is –40°C to +85°C. This device is tested to Bellcore Technical Advisory TA-TSY-000983 at minimum (Ref. 4).

The optical fiber in the mast is a low thermal coefficient of delay (LTCD) fiber manufactured only by Sumitomo (Refs. 5 and 6). It is coated with layers of liquid crystal material having a negative thermal coefficient of expansion and a soft buffer material to achieve a TCD of < 1 part-per-million/°C. Fig. 2 is a plot of the TCD of this optical fiber. It is compatible with Corning SMF-28 and it met our out-gassing requirements. Rifocs, Corporation installed AVIM angle polished connectors on the fiber optic cable. These connectors are designed for rugged applications and have excellent reliability (Ref. 7).

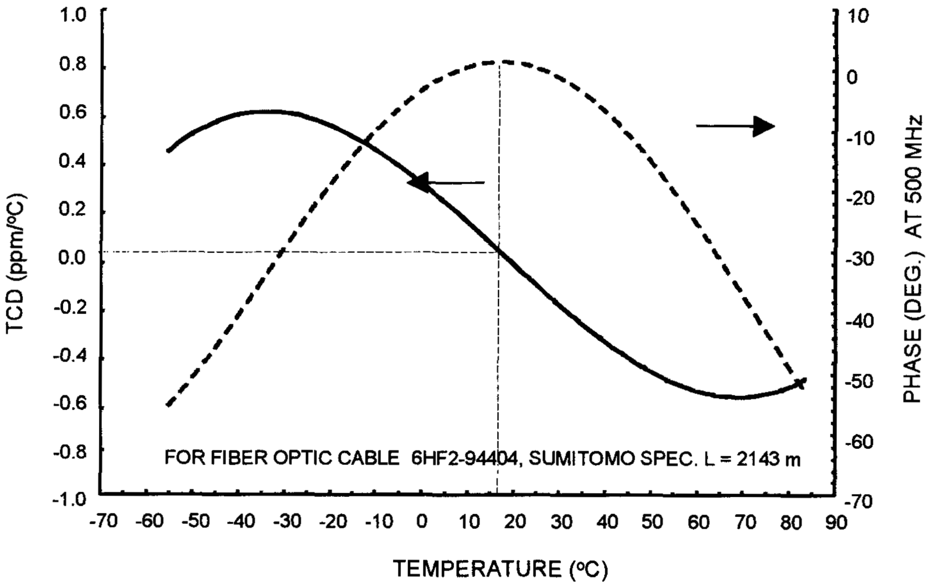

Fig. 2. The TCD for the mast optical fiber.

The variable delay line is a thermally controlled winding of optical fiber. It consists of a thin walled aluminum cylinder which has approximately 260 meters of optical fiber bonded to its outer surface and resistive foil heaters on the inside wall. The base of the aluminum cylinder is heat sunk to the chassis of the fiber optic transmitter module through a fiber glass washer which provides a calibrated thermal resistance. The chassis is bolted to the cooling plate in the spacecraft. The optical fiber is standard single-mode communications fiber manufactured by Spectran.

Thermal expansion or contraction of the aluminum cylinder and optical fiber, and thermally induced change in the index of refraction of the optical fiber all contribute to the delay change through the optical fiber when it is heated or cooled. The phase delay change versus temperature is 59°/°C.

Tests and Results

The fiber optic cable assemblies were tested many times for connector reliability and TCD over a temperature range as wide as –60°C to +85°C. Some cable tests were run in conjunction with testing other parts of the system. In these cases the temperature range was typically from room temperature down to –50°C and then cycled sinusoidally ± 8°C around 50°C. In addition to these tests the flight cables were cycled sinusoidally ± 10°C around –25°C for two weeks.

Two LTCD optical fibers were installed in the mast, one primary and one backup. One of these optical fibers was broken by technicians when they removed and rerouted it. The mast was extended and retracted approximately 32 times. It was extended and retracted once at a temperature of –60°C.

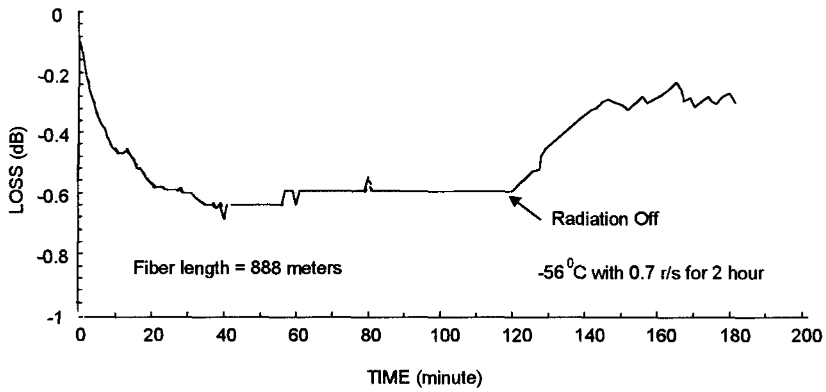

Fig. 3. Radiation induced loss in the LTCD optical fiber at –56°C.

With the exception of the mast fiber that was broken in the rerouting incident, there were no cable or connector failures. One LTCD optical fiber was subjected to ionizing radiation at –60°C. A plot of this data is shown in Fig. 3.

For the thermal vacuum test we placed the fiber optic transmitter, receiver, and optical fibers all in the same vacuum test chamber. Each of these three system components was subjected to a different temperature range. The transmitter was subjected to a sinusoidal temperature variation of ± 10°C over the average temperature range from 5°C to 45°C. The receiver was subjected to a sinusoidal temperature variation of ± 10°C over the average temperature range from -40°C to +15°C. The optical fiber was subjected to sinusoidal temperature variation of 12°C over the average temperature range from –10°C to –60°C.

The stabilized fiber optic link locked up properly and met its 3° phase stability specification over the entire range of test temperatures.

The fiber optic transmitter and receiver were subjected to vibration according to the following tables.

Direction	Frequency (Hz)	Design, Qual Test PF Test	Accept Test
Fiber Optic	20-80	+6.5 dB/octave	+6.5 dB/Octave
Transmitter	80-250	0.10 g^2/Hz	0.04 g^2/Hz
Out of plane	250-350	+20.3dB/octave	+20.3 dB/octave
	350-600	1.0 g^2/Hz	0.4 g^2/Hz
	600-2,000	-13.2 dB/octave	-13.2 dB/octave
	2,000	0.005 g^2/Hz	0.002 g^2/Hz
	overall	22.0 g_{rms}	22.0 g_{rms}
Fiber Optic	20-80	+6.5 dB/Octave	+6.5 dB/Octave
Transmitter	80-200	0.10 g^2/Hz	0.04 g^2/Hz
In plane	200-250	+12.4 dB/octave	+12.4 dB/octave
	250-500	0.25 g^2/Hz	0.10g^2/Hz
	500-2,000	-8.5 dB/octave	-8.5 dB/octave
	2,000	0.005 g^2/Hz	0.002 g^2/Hz
	overall	12.2 g_{rms}	7.7 g_{rms}

Table 1. Fiber optic transmitter vibration test.

Direction	Frequency (Hz)	Design, Qual Test PF Test	Accept Test
Fiber Optic	20-50	+6 dB/octave	
Receiver	50-400	0.2 g^2/Hz	
Out of plane	400-2,000	-7.5 dB/octave	
	overall	11.0 g_{rms}	
Fiber Optic	20-50	+6 dB/octave	+6 dB/octave
Receiver	50-400	0.1 g^2/Hz	0.16 g^2/Hz
In plane	400-2,000	-7.5 dB/octave	-7.5 dB/octave
	overall	15.6 g_{rms}	9.8 g_{rms}

Table 2. Fiber optic receiver vibration test.

Conclusion

The SRTM project had a unique problem with the systems stability that was best resolved with a microwave fiber optic link. A suitable fiber optic link was designed and implemented using primarily COTS hardware with minor modifications where needed to improve reliability. To our knowledge this is the first 1550 nm single-mode fiber optic link to be implemented for use in space.

We extensively tested the stabilized fiber optic link over the entire worst case range of potential environmental conditions including temperature, vacuum, and vibration. It met all of its specifications and worked flawlessly without a single failure in any part.
This work has shown that complex photonic systems implemented with carefully chosen and minimally modified COTS devices can meet the reliability requirements of some space applications.

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